

TITLE OF THE INVENTION

POWER SEMICONDUCTOR DEVICE USED FOR POWER CONTROL

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the
5 benefit of priority from the prior Japanese Patent
Application No. 2003-139071, filed May 16, 2003, the
entire contents of which are incorporated herein by
reference.

BACKGROUND OF THE INVENTION

10 1. Field of the Invention

The present invention relates to a semiconductor
device used for power control. More specifically, the
invention relates to a horizontal power FET (field-
effect transistor) and an SBD (Schottky barrier diode).

15 2. Description of the Related Art

Conventionally a power semiconductor device such
as a switching device and a diode has been used in a
switching power supply, an inverter circuit and the
like. The power semiconductor device needs to be high
20 in breakdown voltage and low in on-resistance.
However, there is a tradeoff, which depends upon device
materials, between the breakdown voltage and the on-
resistance in the power semiconductor device.

In accordance with the advance of technical
25 development, the on-resistance of a power semiconductor
device is lowered to the vicinity of the limit of
electrical resistance of silicon that is the principal

material of the power semiconductor device. It is thus
necessary to change the material in order to lower the
on-resistance further. A power semiconductor device
has recently been proposed which employs a nitride
5 semiconductor such as gallium nitride (GaN) and
aluminum gallium nitride (AlGaN) and a wideband gap
semiconductor such as silicon carbide (SiC) as
switching device materials. A power semiconductor
device using such a wideband gap semiconductor can
10 improve in the above tradeoff that depends upon device
materials and dramatically decrease in on-resistance
(see, for example, N. -Q. Zhang et al., "High Breakdown
GaN HEMT with Overlapping Gate Structure," IEEE
Electron Device Letters, Vol. 21, No. 9, September,
15 2000).

However, when a horizontal power device is formed
of a wideband gap semiconductor, if the breakdown
voltage of a surface passivation insulating film is
low, the breakdown voltage of the device will depend
20 upon the breakdown voltage and the device will be
broken the instant that a voltage higher than the
breakdown voltage of the surface passivation insulating
film is applied to the device. In order to avoid this,
the device is designed to decrease the electric field
25 therein and have an adequate breakdown voltage. Such a
design however makes it impossible to bring about the
capability of the wideband gap semiconductor and

results in increase in on-resistance.

The above device has another problem of having no avalanche capability because the device is broken before an avalanche breakdown occurs.

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BRIEF SUMMARY OF THE INVENTION

A power semiconductor device according to an aspect of the present invention, comprises a first semiconductor layer, a second semiconductor layer of a first conductivity type formed on the first semiconductor layer, first and second main electrodes formed on the second semiconductor layer separately from each other, a control electrode formed on the second semiconductor layer between the first and second main electrodes, and a third semiconductor layer formed on the second semiconductor layer between the control electrode and the second main electrode.

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A power semiconductor device according to another aspect of the present invention, comprises a first semiconductor layer, a second semiconductor layer of a first conductivity type formed on the first semiconductor layer, an anode electrode formed on the second semiconductor layer, the anode electrode and the second semiconductor layer forming a Schottky junction, a cathode electrode formed on the second semiconductor layer and electrically connected to the second semiconductor layer, and a third semiconductor layer formed on the second semiconductor layer between the

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anode electrode and the cathode electrode.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a first embodiment of the present invention;

FIG. 2 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a second embodiment of the present invention;

FIG. 3 is a cross-sectional view schematically showing a configuration of a modification to the horizontal GaN power HEMT according to the second embodiment of the present invention;

FIG. 4 is a cross-sectional view schematically showing a configuration (and dimensions) of the horizontal GaN power HEMT according to the second embodiment of the present invention;

FIG. 5 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a third embodiment of the present invention;

FIG. 6 is a cross-sectional view schematically showing a configuration of a modification to the horizontal GaN power HEMT according to the third embodiment of the present invention;

FIG. 7 is a cross-sectional view schematically

showing a configuration of a horizontal GaN power HEMT according to a fourth embodiment of the present invention;

5 FIG. 8 is a cross-sectional view schematically showing a configuration of a modification to the horizontal GaN power HEMT according to the fourth embodiment of the present invention;

10 FIG. 9 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a fifth embodiment of the present invention;

15 FIG. 10 is a cross-sectional view schematically showing a configuration of a first modification to the horizontal GaN power HEMT according to the fifth embodiment of the present invention;

 FIG. 11 is a cross-sectional view schematically showing a configuration of a second modification to the horizontal GaN power HEMT according to the fifth embodiment of the present invention;

20 FIG. 12 is a cross-sectional view schematically showing a configuration (and dimensions) of the second modification to the horizontal GaN power HEMT according to the fifth embodiment of the present invention;

25 FIG. 13 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a sixth embodiment of the present invention;

FIG. 14 is a cross-sectional view schematically showing a configuration of a first modification to the horizontal GaN power HEMT according to the sixth embodiment of the present invention;

5 FIG. 15 is a cross-sectional view schematically showing a configuration (and dimensions) of the first modification to the horizontal GaN power HEMT according to the sixth embodiment of the present invention;

10 FIG. 16 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a seventh embodiment of the present invention;

15 FIG. 17 is a cross-sectional view schematically showing a configuration of a first modification to the horizontal GaN power HEMT according to the seventh embodiment of the present invention;

20 FIG. 18 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to an eighth embodiment of the present invention;

FIG. 19 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a ninth embodiment of the present invention;

25 FIG. 20A is a cross-sectional view schematically showing a configuration of the horizontal GaN power HEMT according to the ninth embodiment of the present

invention;

FIG. 20B is a band gap chart taken along line A-A' of FIG. 20A;

FIG. 21 is a cross-sectional view schematically showing a configuration of a modification to the horizontal GaN power HEMT according to the ninth embodiment of the present invention;

FIG. 22 is a cross-sectional view schematically showing a configuration of a horizontal GaN power HEMT according to a tenth embodiment of the present invention;

FIG. 23 is a cross-sectional view schematically showing a configuration of a horizontal GaN-SBD according to an eleventh embodiment of the present invention; and

FIG. 24 is a cross-sectional view schematically showing a configuration of a modification to the horizontal GaN-SBD according to the eleventh embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention will now be described with reference to the accompanying drawings. The same elements are indicated by the same reference numerals throughout the drawings.

First Embodiment

First of all, a power semiconductor device according to a first embodiment of the present

invention will be described.

FIG. 1 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the first embodiment. The horizontal GaN power HEMT is a power HEMT (high electron mobility transistor) in which source and drain electrodes are formed horizontally on the surface of a substrate and gallium nitride (GaN) is used for a channel layer.

The HEMT has the following configuration. As shown in FIG. 1, an undoped GaN layer 12 of an intrinsic semiconductor (i-type semiconductor) layer is formed as a channel layer on a substrate 11. An n-type AlGaIn layer 13 of an n-type semiconductor layer is formed as a barrier layer on the GaN layer 12. For example, SiC or sapphire is used for the substrate 11. The impurity concentration of the GaN layer 12 has only to be $1.0 \times 10^{14} \text{ cm}^{-3}$ or lower and allows a necessary breakdown voltage to be held in the HEMT.

Source and drain electrodes 14 and 15 are formed on the n-type AlGaIn layer 13 separately from each other. A gate electrode 16 is formed on the n-type AlGaIn layer 13 between the source and drain electrodes 14 and 15. An undoped GaN layer 17 of an intrinsic semiconductor (i-type semiconductor) layer is formed on the n-type AlGaIn layer 13 between the gate and drain electrodes 16 and 15. The surface of the device (the surface of the GaN layer 17) is covered with an

insulation film 18, e.g., a SiO₂ film deposited by CVD or the like. The source electrode 14, drain electrode 15 and gate electrode 16 are each formed of a multilayer film of Ti/Al/Ni/Au.

5 The above-described GaN layers 12 and 17 and n-type AlGaIn layer 13 are each a semiconductor having a wideband gap of 3 eV or more. The critical field of the wideband gap semiconductor is not less than ten times as high as that of silicon (Si). For example,
10 the critical field of 4H-SiC is 3×10^6 V/cm, that of GaN is 5×10^6 V/cm and that of diamond is 8×10^6 V/cm to 10×10^6 V/cm.

 Since the SiO₂ film that forms the insulation film 18 is poor in quality, its breakdown voltage will be
15 lower than that (1×10^7 V/cm) of a good-quality thermal oxide film. Thus, the breakdown voltage of the insulation film 18 greatly depends upon the process.

 In a conventional wideband gap semiconductor device, the critical fields of a semiconductor layer
20 and a surface passivation film are close to each other; hence, the question of which of the semiconductor layer and the surface passivation film is broken greatly depends upon the quality of an insulation film that forms the surface passivation film. When the
25 insulation film is deposited, there is a possibility that the substrate will warp and the insulation film will crack and come off by stress due to a difference

in thermal expansion coefficient between the insulation film and the semiconductor layer. For this reason, there is a limit to the thickness of the insulation film.

5 Since the power HEMT according to the first embodiment, shown in FIG. 1, employs a nitride semiconductor as a device material, it has a high critical field and a high breakdown voltage. Furthermore, the GaN layer 17 is formed in that portion
10 between the gate and drain to which a high voltage is applied, thereby decreasing the electric field applied to the insulation film 18. Thus, the breakdown voltage of the device does not depend upon the breakdown
15 voltage of the insulation film 18 but the critical field of the semiconductor layer (n-type AlGa_N layer 13 or GaN layer 17).

 In the configuration of the device according to the first embodiment, a stable critical field can be achieved by forming a surface passivation film by the
20 GaN layer 17 of a crystal growth film. The electric field applied to the insulation film 18 can be weakened by increasing the length of the surface of the
 semiconductor between the gate and drain, which is covered with the insulation film 18, thereby generating
25 a stable breakdown voltage. Since the crystal growth film is used, no problem of stress occurs but the thickness of the GaN layer 17 can freely be determined.

As one method of increasing the above length of the surface of the semiconductor layer, a trench can be formed between the gate and drain. In this method, however, a drift layer through which current flows will be lengthened and the on-resistance will be increased. In the configuration of the first embodiment, however, no influence is exercised on a drift portion through which current flows and thus a stable breakdown voltage can be generated without increasing the on-resistance.

In the configuration shown in FIG. 1, the gate and drain electrodes 16 and 15 are formed separately from the undoped GaN layer 17. However, the electrodes 16 and 15 can be formed in contact with the layer 17.

As described above, according to the first embodiment, not the insulation film but the GaN layer 17 of a semiconductor layer is formed in that portion between the gate and drain electrodes 16 and 15 to which a high voltage is applied. Consequently, the same critical field as that of the drift portion can be expected and a stable breakdown voltage can be generated.

Second Embodiment

A power semiconductor device according to a second embodiment of the present invention will now be described.

FIG. 2 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according

to the second embodiment. The same elements as those of the first embodiment are indicated by the same reference numerals and their descriptions are omitted. Only different elements will be described below.

5 As illustrated in FIG. 2, a p-type GaN layer 19 of a p-type semiconductor layer is formed on an undoped GaN layer 17. An insulation film 18 is formed on the undoped GaN layer 17 and p-type GaN layer 19. A field plate electrode 20 is formed on the p-type GaN layer 19
10 from which the insulation film 18 is removed and electrically connected to a source electrode 14. The electrode 20 is formed of, e.g., a Pt film.

 In the semiconductor device so configured, the p-type GaN layer 19 is formed. Therefore, when a high
15 voltage is applied to a drain electrode 15, a junction between the p-type GaN layer 19 and the undoped GaN layer 17 exhibits a high electric field and an avalanche breakdown occurs. The holes caused by the avalanche breakdown are quickly discharged into the
20 p-type GaN layer 19; hence, a high avalanche capability can be achieved.

 The field plate electrode 20 formed between the gate and drain is connected to the source electrode 14. Thus, the gate-to-drain capacitance decreases and the
25 switching speed increases.

 FIG. 3 is a cross-sectional view of a modification to the second embodiment of the present invention. In

the configuration shown in FIG. 2, the field plate electrode 20 is connected to the source electrode 14. In the configuration of the modification shown in FIG. 3, the field plate electrode 20 is connected to the gate electrode 16. This configuration allows the field plate electrode 20 and gate electrode 16 to be formed integrally or by a single deposition and a patterning step. Accordingly, the process can be simplified.

When the field plate electrode 20 shown in FIGS. 2 and 3 is formed, it is desirable that the thickness t of the undoped GaN layer 17 be smaller than the distance L between the gate and drain as shown in FIG. 4. With this configuration, the electric field generated under the p-type GaN layer 19 alongside the drain electrode 15 becomes greater than that generated near the gate electrode 16. For this reason, an avalanche breakdown occurs near the p-type GaN layer 19 and the holes caused at the time of the avalanche breakdown are quickly discharged into the p-type GaN layer 19. Consequently, a high avalanche capability can be achieved in the configuration shown in FIG. 4.

Third Embodiment

A power semiconductor device according to a third embodiment of the present invention will now be described.

FIG. 5 is a cross-sectional view showing a

configuration of a horizontal GaN power HEMT according to the third embodiment. The same elements as those of the second embodiment shown in FIG. 2 are indicated by the same reference numerals and their descriptions are omitted. Only different elements will be described below.

Referring to FIG. 5, a thick insulation film 21 is formed on an undoped GaN layer 17 and part of a p-type GaN layer 19. A field plate electrode 20 is formed on the p-type GaN layer 19 and the insulation film 21.

The third embodiment described above produces the same advantage as that in the case of a two-step field plate structure. In this case, some voltages are applied to the insulation film 21; therefore, it is desirable that the insulation film 21 have such a thickness that it is not broken by the above voltages.

FIG. 6 is a cross-sectional view of a modification to the third embodiment. As shown in FIG. 6, the undoped GaN layer 17 is formed to have two steps (or to vary in thickness). A field plate electrode 20 is formed on the higher surface of the GaN layer 17 with an insulation film 22 interposed therebetween. The field plate electrode 20 is electrically connected to a source electrode 14.

Even though the thickness of the undoped GaN layer 17 varies in two steps as described above, the same advantage as that of the second embodiment can be

obtained. In this case, a voltage is hardly applied to the insulation film 22 and thus the insulation film 22 has only to be thinner than the insulation film 21.

Fourth Embodiment

5 A power semiconductor device according to a fourth embodiment of the present invention will now be described.

FIG. 7 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the fourth embodiment. The same elements as those of the first embodiment shown in FIG. 1 are indicated by the same reference numerals and their descriptions are omitted. Only different elements will be described below.

15 As shown in FIG. 7, a p-type GaN layer 23 is formed on an n-type AlGaIn layer 13, between a gate electrode 16 and an undoped GaN layer 17, and close to the GaN layer 17. An insulation film 18 is formed on the GaN layer 17 and part of the p-type GaN layer 23.

20 Furthermore, a field plate electrode 20 that is electrically connected to a source electrode 14 is formed on the insulation film 18 and p-type GaN layer 23. In other words, the field plate electrode 20 is formed so as to cover the p-type GaN layer 23 and part

25 of the insulation film 18.

In the semiconductor device so configured, the undoped GaN layer 17 is formed under the field plate

electrode 20 irrespective of the location of the p-type GaN layer 23. Consequently, the undoped GaN layer 17 performs the same function as that of the insulation film under the field plate electrode 20, thus
5 generating a stable breakdown voltage.

FIG. 8 is a cross-sectional view of a modification to the horizontal GaN power HEMT according to the fourth embodiment. As illustrated in FIG. 8, an insulation film 24 that varies in thickness is formed
10 on the undoped GaN layer 17. A field plate electrode 20 that is electrically connected to the source electrode 14 is formed on the insulation film 24 and the p-type GaN layer 23. Thus, a two-step field plate structure can be formed using the insulation film 24
15 that varies in thickness.

Fifth Embodiment

A power semiconductor device according to a fifth embodiment of the present invention will now be described.

20 FIG. 9 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the fifth embodiment. The same elements as those of the second embodiment shown in FIG. 2 are indicated by the same reference numerals and their descriptions are
25 omitted. Only different elements will be described below.

Referring to FIG. 9, contact layers 25 and 26 are

formed under source and drain electrodes 14 and 15, respectively. The contact layers 25 and 26 are each formed of, e.g., an n^+ -type GaN layer.

In the semiconductor device so configured,
5 the contact layers 25 and 26 allow contact resistance to decrease between each of the source and drain electrodes 14 and 15 and an undoped GaN layer 12. Low on-resistance can thus be achieved.

The contact layers 25 and 26 can be formed by
10 forming a trench in each of the undoped GaN layer 12 and n-type AlGaIn layer 13 by etching and then growing the n^+ -type GaN layer in the trench.

FIG. 10 is a cross-sectional view of a first
modification to the fifth embodiment of the present
15 invention. As shown in FIG. 10, the contact layer 26 and undoped GaN layer 17 are formed so as to overlap each other in their height direction. Since the surface of the contact layer 26 is partly covered with the undoped GaN layer 17, the electric field of the
20 surface of the undoped GaN layer 17 or the electric field of the insulation film 18 is weakened and a stable breakdown voltage can be generated. In this configuration, the undoped GaN layer 17 can be formed by crystal growth by CVD or the like after the contact
25 layers 25 and 26 are formed.

FIG. 11 is a cross-sectional view of a second modification to the fifth embodiment. As shown in

FIG. 11, the p-type GaN layer 19 and contact layer 26 are formed so as to overlap each other in their height direction. In this configuration, the overlapping portion of the layers 19 and 26 exhibits the highest electric field and the electric fields of the undoped GaN layer 17 and insulation film 18, which are located outside the overlapping portion, can be decreased. Thus, the semiconductor device of the second modification can generate a stable breakdown voltage.

In the configuration of the device of the second modification, as shown in FIG. 12, it is desirable that the thickness t of the undoped GaN layer 17 be smaller than the distance d between the gate electrode 16 and the contact layer 26. The electric field generated under the p-type GaN layer 19 alongside the drain electrode 15 becomes greater than the electric field generated close to the gate electrode, and the holes generated at the time of an avalanche breakdown are quickly discharged into the p-type GaN layer 19. Consequently, a high avalanche capability can be achieved in the configuration shown in FIG. 12.

In the configurations shown in FIGS. 9 to 12, the contact layers 25 and 26 are buried into the n-type AlGaIn layer 13. However, these contact layers 25 and 26 can selectively be formed on the n-type AlGaIn layer 13.

Sixth Embodiment

A power semiconductor device according to a sixth embodiment of the present invention will now be described.

5 FIG. 13 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the sixth embodiment. The same elements as those of the second embodiment shown in FIG. 2 are indicated by the same reference numerals and their descriptions are
10 omitted. Only different elements will be described below.

 As illustrated in FIG. 13, a drain electrode 15 is covered with an undoped GaN layer 17. More specifically, the drain electrode 15 is formed on an n-type
15 AlGaIn layer 13 and the undoped GaN layer 17 is formed on the drain electrode 15. A p-type GaN layer 19 is formed on part of the undoped GaN layer 17 and an insulation film 18 is formed on the undoped GaN layer 17 and p-type GaN layer 19. Moreover, a field plate
20 electrode 20 is formed on the p-type GaN layer 19 from which the insulation film 18 is removed. The field plate electrode 20 is electrically connected to a source electrode 14.

 In the power semiconductor device so configured,
25 the electric field that is applied to the insulation film 18 deposited on the surface of the undoped GaN layer 17 can be almost zero. The breakdown voltage of

the device therefore completely depends upon the semiconductor layer of the undoped GaN layer 17 or the n-type AlGaIn layer 13. The configuration can be obtained by forming the drain electrode 15 by high-melting metal such as tungsten (W) and then growing the undoped GaN layer 17 on the drain electrode 15.

FIG. 14 is a cross-sectional view of a first modification to the sixth embodiment. As shown in FIG. 14, the drain electrode 15 and p-type GaN layer 17 are formed so as to overlap each other in their height direction. In other words, the drain electrode 15 is completely covered with the p-type GaN layer 19. If the drain electrode 15 is done so, a high-voltage section is confined within crystal (GaN layer 17); therefore, a voltage is hardly applied to the insulation film 18 outside the layer 17. Consequently, the materials for the insulation film 18 formed on the GaN layer 17 can be selected considerably freely.

In the configuration of the first modification, as shown in FIG. 15, it is desirable that the thickness t of the undoped GaN layer 17 be smaller than the distance between the gate and drain electrodes 16 and 15. Thus, the breakdown voltage of the device depends upon the thickness t of the undoped GaN layer 17 and the breakdown voltage can precisely be controlled by the undoped GaN layer 17 of a crystal growth film.

Seventh Embodiment

A power semiconductor device according to a seventh embodiment of the present invention will now be described.

5 FIG. 16 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the seventh embodiment. The same elements as those of the first embodiment shown in FIG. 1 are indicated by the same reference numerals and their descriptions
10 are omitted. Only different elements will be described below.

 Referring to FIG. 16, an insulation film 18 is deposited on the surface of an undoped GaN layer 17. A field plate electrode 20 is selectively formed on the
15 insulation film 18. The field plate electrode 20 is connected to a source electrode 14.

 In the power semiconductor device so configured, the undoped GaN layer 17 is formed on an n-type AlGaIn layer 13 and thus an electric field applied to the
20 insulation film 18 can be lessened. Moreover, the field plate electrode 20 is formed on the insulation film 18 and thus a leakage current flowing from the field plate electrode 20 into the undoped GaN layer 17 can be reduced to an extreme.

25 In the configuration shown in FIG. 16, the field plate electrode 20 is electrically connected to the source electrode 14. The gate-to-drain capacitance can

be decreased and the switching speed can be improved.
As compared with the configuration including the p-type
GaN layer 19, an avalanche capability is lowered but a
stable breakdown voltage can be generated and the
5 process can be simplified.

In the configuration shown in FIG. 16, the field
plate electrode 20 is formed on the insulation film 18.
However, the field plate electrode 20 can directly be
formed on the undoped GaN layer 17 to form a Schottky
10 barrier between the undoped GaN layer 17 and the field
plate electrode 20. In this case, the leakage current
from the field plate electrode 20 increases, but the
advantage of lessening the electric field applied to
the insulation film 18 formed on the surface of the
15 device can be obtained.

FIG. 17 is a cross-sectional view of a first
modification to the seventh embodiment of the present
invention. As illustrated in FIG. 17, the field plate
electrode 20 is formed integrally with the gate
20 electrode 16 as one component and these electrodes 20
and 16 are electrically connected to each other. The
integral formation therefore simplifies the process.

Eighth Embodiment

A power semiconductor device according to an
25 eighth embodiment of the present invention will now be
described.

FIG. 18 is a cross-sectional view showing a

configuration of a horizontal GaN power HEMT according to the eighth embodiment. The same elements as those of the second embodiment shown in FIG. 2 are indicated by the same reference numerals and their descriptions are omitted. Only different elements will be described below.

As shown in FIG. 18, a gate insulation film 27 is formed under a gate electrode 16. Thus, a gate leakage current can be reduced drastically and consequently a loss of a gate driving circuit can be decreased. The gate insulation film 27 is formed of AlGaOx obtained by oxidizing an AlGaN layer, SiN, AlN and Al₂O₃ that are deposited, and the like.

Ninth Embodiment

A power semiconductor device according to a ninth embodiment of the present invention will now be described.

FIG. 19 is a cross-sectional view showing a configuration of a horizontal GaN power HEMT according to the ninth embodiment. As the power HEMTs according to the first to eighth embodiments, the power HEMT according to the ninth embodiment is formed to have a heterojunction of n-type AlGaN/GaN.

As illustrated in FIG. 19, an undoped GaN layer 12 of an intrinsic semiconductor (i-type semiconductor) layer is formed as a channel layer on a substrate 11. An n-type Al_{0.1}Ga_{0.9}N layer 31 of an n-type

semiconductor layer is formed as a barrier layer on the GaN layer 12. For example, SiC or sapphire is used for the substrate 11. The impurity concentration of the GaN layer 12 has only to be $1.0 \times 10^{14} \text{ cm}^{-3}$ or lower and allows a necessary breakdown voltage to be held in the HEMT.

Source and drain electrodes 14 and 15 are formed on the n-type $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 31 separately from each other. A gate electrode 16 is formed on the n-type $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 31 between the source and drain electrodes 14 and 15. An undoped $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 32 is formed on the n-type $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 31 between the gate and drain electrodes 16 and 15.

A p-type AlGaN layer 33 of a p-type semiconductor layer is formed on the undoped $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 32 and the device surface (the surface of the undoped $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ layer 32 and that of the p-type AlGaN layer 33) is covered with an insulation film 18. The insulation film 18 formed on the p-type AlGaN layer 33 is partly removed and a field plate electrode 20 is formed on the p-type AlGaN layer 33 from which the insulation film 18 is removed. Furthermore, the field plate electrode 20 and source electrode 14 are electrically connected to each other.

In the power semiconductor device so configured, if the percentage of Al in the n-type AlGaN layer 31 and that of Al in the undoped AlGaN layer 32 are made

equal to each other, electrons quickly flow into the n-type AlGa_N layer 31 to achieve a high avalanche capability even when an avalanche breakdown occurs in the undoped AlGa_N layer 32.

5 According to the first to eighth embodiments shown in FIGS. 1 to 18, a gate-to-drain semiconductor layer is formed of the undoped Ga_N layer 17. Lattice distortion is therefore small and the undoped Ga_N layer 17 can be thickened by crystal growth. In the ninth
10 embodiment, if the percentage of Al in the undoped AlGa_N layer 32 between the gate and drain increases, lattice distortion becomes large and thus a crack is easy to occur. However, the undoped AlGa_N layer 32 needs to be thickened to some extent in order to
15 maintain the breakdown voltage.

 As shown in the band gap chart in FIG. 20B, if the percentage of Al in the undoped AlGa_N layer 32 gradually decreases toward the p-type AlGa_N layer 33, it is possible to achieve a configuration that
20 eliminates band discontinuity between the AlGa_N layer 32 and n-type AlGa_N layer 31 while maintaining the same lattice distortion as that caused when the percentage of Al is equivalently small. The band gap chart shown in FIG. 20B corresponds to a section taken along line
25 A - A' in FIG. 20A.

 FIG. 21 is a cross-sectional view of a modification to the ninth embodiment. As illustrated

in FIG. 21, a p-type GaInN layer 34 of a p-type semiconductor layer is formed on an undoped GaN layer 17. In this configuration, since the p-type GaInN layer 34 has a band gap that is narrower than that of a GaN layer, there is no barrier to the holes. Consequently, the holes caused at the time of an avalanche breakdown can quickly be discharged and an avalanche capability can be increased more than that in the configuration including a GaN layer.

10 Tenth Embodiment

A power semiconductor device according to a tenth embodiment of the present invention will now be described. The tenth embodiment is directed to an example of a horizontal power MISFET using diamond.

15 FIG. 22 is a cross-sectional view showing a configuration of the horizontal diamond MISFET according to the tenth embodiment.

The configuration of the MISFET is as follows. As shown in FIG. 22, an undoped diamond layer 35 of an intrinsic semiconductor (i-type semiconductor) is formed as a channel layer on a substrate 11. A p-type diamond layer 36 of a p-type semiconductor layer is formed as a barrier layer on the undoped diamond layer 35. The substrate 11 is formed using diamond and the like. The impurity concentration of the undoped diamond layer 35 has only to be $1.0 \times 10^{14} \text{ cm}^{-3}$ or lower and allows a necessary breakdown voltage to be

held in the MISFET.

Source and drain electrodes 14 and 15 are formed on the p-type diamond layer 36 separately from each other. A gate insulation film 27 is formed on the p-type diamond layer 36 between the source and drain electrodes 14 and 15. A gate electrode 16 is formed on the gate insulation film 27. An undoped diamond layer 37 of an intrinsic semiconductor (i-type semiconductor) layer is formed on the p-type diamond layer 36 between the gate and drain electrodes 16 and 15.

An n-type diamond layer 38 of an n-type semiconductor layer is formed on the undoped diamond layer 37. An insulation film 18 is formed on the undoped diamond layer 37 and n-type diamond layer 38 (device surface). The insulation film 18 is partly removed from the surface of the n-type diamond layer 38 and a field plate electrode 20 is formed on the n-type diamond layer 38 from which the insulation film 18 is removed. The field plate electrode 20 is electrically connected to the source electrode 14.

Even in the tenth embodiment that is directed to a horizontal power MISFET or MESFET formed using diamond, the critical field of a semiconductor layer can be increased as in the GaN-HEMT described above. Since, however, the breakdown voltage of an insulation film formed on the device surface greatly depends upon the process and materials, it is difficult to fully bring

about the capability of the semiconductor layer.
Therefore, even in the MISFET using diamond, a stable
breakdown voltage can be generated by forming the
undoped diamond layer 37 serving as an insulation film
5 under the field plate electrode 20.

The MISFET according to the tenth embodiment can
also be configured to have a heterojunction of
AlGaN/GaN, such as the foregoing field plate electrode,
a contact layer and a two-step field plate structure.

10 Eleventh Embodiment

A power semiconductor device according to an
eleventh embodiment of the present invention will now
be described.

FIG. 23 is a cross-sectional view showing a
15 configuration of a horizontal GaN-SBD according to the
eleventh embodiment. The horizontal GaN-SBD is a power
Schottky barrier diode in which anode and cathode
electrodes are horizontally formed on the surface of a
substrate and a channel layer is formed of gallium
20 nitride (GaN).

The configuration of the SBD is as follows. As
illustrated in FIG. 23, an undoped GaN layer 12 of an
intrinsic semiconductor (i-type semiconductor) layer is
formed as a channel layer on a substrate 11. An n-type
25 AlGaN layer 13 of an n-type semiconductor layer is
formed as a barrier layer on the GaN layer 12. The
substrate 11 is formed of SiC, sapphire or the like.

The impurity concentration of the GaN layer 12 has only to be $1.0 \times 10^{14} \text{ cm}^{-3}$ or lower and allows a necessary breakdown voltage to be held in the SBD.

5 Anode and cathode electrodes 41 and 42 are formed on the n-type AlGaIn layer 13 separately from each other. An undoped GaN layer 17 of an intrinsic semiconductor (i-type semiconductor) layer is formed on the n-type AlGaIn layer 13 between the anode and cathode electrodes 41 and 42. Furthermore, a p-type GaN layer 10 19 of a p-type semiconductor layer is formed on the undoped GaN layer 17. The undoped GaN layer 17 and p-type GaN layer 19 (device surface) are covered with an insulation film 18. The insulation film 18 is partly removed from the surface of the p-type GaN layer 15 19 and a field plate electrode 20 is formed on the p-type GaN layer 19 from which the insulation film 18 is removed.

In the SBD so configured, the field plate electrode 20 is formed in order to prevent a breakdown voltage from lowering between the anode and cathode 20 electrode 41 and 42. As in the foregoing power HEMT, the undoped GaN layer 17 serving as an insulation film is formed under the field plate electrode 20. Thus, a high breakdown voltage SBD can be achieved while 25 maintaining a low on-resistance.

FIG. 24 shows a section of a modification to the power semiconductor device according to the eleventh

embodiment. Referring to FIG. 24, the field plate electrode 20 is formed integrally with the anode electrode 41 as one component and these electrodes 20 and 41 are electrically connected to each other.

5 As described above, the integral formation of the field plate electrode 20 and anode electrode 41 simplifies the process. The holes generated at the time of an avalanche breakdown are quickly discharged into the anode electrode 41 from the field plate
10 electrode 20. Consequently, a high avalanche capability can be achieved.

 In the configurations shown in FIGS. 23 and 24, it is desirable that the thickness of the undoped GaN layer 17 be smaller than the distance between the anode
15 and cathode electrodes 41 and 42 in order to control the breakdown voltage with reliability.

 The eleventh embodiment is directed to an SBD using GaN in a semiconductor layer. However, it can be applied to an SBD using diamond.

20 As described above, according to the embodiments of the present invention, there can be provided a power semiconductor device capable of bringing about the capability of a wideband gap semiconductor device to achieve a low on-resistance and having a high avalanche
25 capability. In other words, there can be provided a high breakdown voltage, very low on-resistance, horizontal wideband gap semiconductor device having a

stable breakdown voltage and a high avalanche capability.

The present invention is not limited to the above first to eleventh embodiments. It can be applied to all of modifications that can easily be obtained by the inventor(s) of the present invention.

The device is formed to have a heterojunction of AlGaIn/GaN; however, it can be formed to have a heterojunction of AlGaInN/GaInN containing In. The relationship in band gap between the respective layers in the HEMT structure can be established. Moreover, the substrate serving to form an AlGaIn heterojunction can be formed of GaN and Si as well as SiC and sapphire.

The embodiments of the present invention are not limited to an HEMT, an MESFET, an MISFET or an SBD but can be applied to a unipolar device such as a JFET and a bipolar device such as a pin diode and an IGBT if the device is a horizontal one.

According to the embodiments of the present invention described above, there can be provided a power semiconductor device having a high avalanche capability and capable of achieving a high breakdown voltage and a low on-resistance.

Additional advantages and modifications will readily occur to those skilled in the art. Therefore, the invention in its broader aspects is not limited to

the specific details and representative embodiments
shown and described herein. Accordingly, various
modifications may be made without departing from the
spirit or scope of the general inventive concept as
5 defined by the appended claims and their equivalents.